

orchard by hanging them against the tree or suspending from the branches. Thermometers should be exposed where the sun will not strike them and where they will have a free circulation of air, but always with a light protection over them to prevent too free radiation of heat from the instrument itself to the sky or other object. A thermometer hung out in the open will, in the sunshine, give a temperature much higher than that of the atmosphere, and at night it will be several degrees colder than the temperature of the air that surrounds it.

(y) *Prospective extension of the fruit-frost service and warning service.*—A few additional fruit-frost stations will be established in Ohio and steps will be taken to give the regular and special "frost warning" service to any fruit section or market-gardening section in the State where action is being taken to protect from frost damage.

## VI.

## AIR DRAINAGE EXPLAINED.

By CHARLES FREDERICK MARVIN, Chief of Bureau.

[Dated Weather Bureau, Washington, D. C., Nov. 20, 1914.]

1. Orchardists and others engaged or interested in agricultural pursuits, as well as physicists and meteorologists often employ the expression "air drainage" to designate certain features of atmospheric circulation attending the occurrence of frost during clear, still, cool nights in regions characterized by hill and valley conditions of topography. The popular conception of the actual phenomenon in question is often technically incorrect, and it seems worth while, therefore, to explain this particular species of atmospheric circulation in some detail in order that forecasters interested in the issue of frost warnings and orchardists and others who are prepared to prevent frost injuries by artificial protective measures may have a proper understanding of this interesting circulation. The faulty conception of air drainage is often conveyed by some such condensed statement as the following: "The air on the higher slopes, cooled by contact with the surface soil or vegetal cover which is itself cooled by the active radiation under clear skies, flows or drains downhill substantially as water would flow on the same slope." This analogy of the flow of water is not materially inexact under particular conditions, but it is especially inappropriate and misleading as applied to the circulation of the air during the nighttime in such hill and valley regions as are now under consideration and that are frequently devoted to orchard and garden purposes. Air drainage on a hillside is *not* like the flow of water on the same slope because (1) air is a compressible gas and its flow is influenced by important thermodynamic actions as well as by gravity while the flow of water which is an incompressible liquid is determined practically by gravity alone; (2) water in place may flow completely away leaving the space it occupied vacant as regards water. Air, however, on a hillside, for example, can only change places with some other air, and then only under specific and prescribed conditions.<sup>1</sup>

2. In what follows an effort is made to clearly describe the interesting type of circulation commonly designated air drainage and to indicate the physical laws in operation.

The author realizes that the explanation of air drainage now offered is at variance with the water-like-flow theory commonly entertained and found superficially discussed in even the best textbooks. This theory, nevertheless, is fallacious as applied to the conditions now under consideration, and will not stand critical analysis. It completely fails to explain the development of the vertical inversion of temperature. It asserts that a stream of cold surface air flows down the slope, filling up the valley with frigid air. How can there be a *thermal belt* on the hillsides if such a water-like flow of cold air exists? How can the alleged water-like flow of cold surface air on the hillside keep one part of the hillside warm and yet fill the whole valley below this level with much colder air? The *reductio ad absurdum* of this theory is brought out by the question: How can a stream of cold surface air flowing in a water-like fashion down a hillside produce a region like the so-called thermal belt that is warmer than any other locality, and how can the same stream flowing onward fill the whole valley below the thermal belt with frigid air?

3. While great diversities prevail in the topographic character of different regions causing corresponding modifications in the local circulation, yet the same general principles operate in all cases and a connected statement of the essential features under simple representative conditions will suffice. Consider, for example, an ordinary extensive valley, such as is to be found almost anywhere in a hilly, rolling country. The sides of the valley, as a rule, will be relatively steep, especially as compared with the bottom or floor, which for the present purposes may be regarded as comparatively level, although in fact it also slopes gently downward, as evidenced by the onward flow of a stream or river of water that may be found therein.

4. Observations tell us that during clear, still nights valleys of this character fill up to a considerable depth with a great riverlike mass of cold air. The temperature is lowest at the bottom, increasingly warmer at intermediate layers and warmest at the surface of the aerial river. Above the river the temperature of the air decreases more or less rapidly with increase of elevation. The term "air drainage" from the present point of view, is the name assigned to the local circulation that is able to create and to build up during a nighttime a deep river, or lakelike mass of cold air similar to that just described.

5. We may for a moment consider another species of air drainage, namely, the sluggish flow of the whole river of cold air down the nearly level floor of the valley on its way to the sea. This sluggish flow does take place and is fairly like that of water. Also in the afternoons and early evenings, while the surface air is still warm and the surface temperature gradient is not as yet strongly nonadiabatic, the flow of cooling surface air even on the steeper slopes may somewhat resemble the flow of water on the same slopes. Nevertheless, both the sluggish flow of the river of cold air and the waterlike flow of portions of surface air in the afternoons constitute for the orchardist relatively unimportant species or aspects of air drainage and need no further mention here.

6. In order to fully understand the circumstances leading to the formation of the river of cold air, it is necessary to begin with a brief account of the condition of the air in and over the valley during the preceding day and incidentally to explain the significance of the adiabatic relation of atmospheric temperatures.

7. In the course of a bright, sunshiny day with little or no wind, the free air occupying the lower strata of the atmosphere for a depth of one or two thousand feet or more, is practically in adiabatic equilibrium, which means

<sup>1</sup> Prof. W. R. Blair, in his Five Year Summary of Free Air Data, Bulletin Mount Weather Observatory, 1913, 6: 118-124, devotes some space to the discussion of mountain and valley temperatures in the vicinity of Mount Weather, and very correctly indicates the kind of circulation that can occur in such regions. In the present paper I am applying the term "air drainage," even though it be a misnomer, to the whole characteristic circulation of air on clear nights in hill and valley regions, whereas Prof. Blair, without specifically declaring himself on the point in question, has limited his use of the term to a real waterlike flow of air that may sometimes take place on relatively gentle slopes.

that the air temperature will fall approximately 1.6°F. for each 300-foot increase of elevation. These strata get into this condition because this is approximately the rate at which a heated mass of air and vapor will cool when it ascends in the free air and expands and does work in pushing aside the surrounding air, but *without any condensation of vapor or any gain from or loss of heat to its environment*. When, therefore, the air in contact with the heated soil and vegetation becomes overheated relative to the surrounding air it ascends, cooling at the adiabatic rate and comes to rest, possibly at an elevated point, where its own temperature and that of the surrounding air are the same. After this convective circulation has continued actively for several hours during a bright, sunshiny day, a considerable portion of the free lower strata not only acquires large additions of heat, but also attains nearly or quite the adiabatic condition of equilibrium. Nevertheless, adiabatic equilibrium is exceptional and limited, both as regards the amount of air involved and the length of time the condition will be maintained. In fact, it may be said that nearly every influence affecting the temperature of air masses opposes the attainment of the adiabatic relation of temperatures. The nonadiabatic state therefore is the rule. In the nonadiabatic atmosphere the air higher up is potentially too warm; *vice versa*, the air lower down is potentially too cold to be in the adiabatic relation. In the nonadiabatic atmosphere, therefore, the warmer air higher up acts as a ceiling and stops the ascent of air from below that has been slightly heated. Conversely, the colder air lower down acts as a floor and effectually stops the descent of air from above that has been slightly cooled.

8. These relatively intangible thermodynamic principles wholly govern and determine the flow of air in the hill and valley regions we are now considering. A steep hillside down which water would flow in the most tumultuous fashion is not a hillside for the flow of air in any sense of the word. The hillside may be replaced by a tremendous cliff with a vertical face, but the effect on the flow of the air will be immaterial in so far as the change in the angle of the slope is concerned. *The function of the hillside in connection with the phenomenon of air drainage is simply that of a cooling agent.* In order to explain this action clearly we need to consider further the surface and free-air temperatures and the cooling influences due to radiation.

9. Even though the free air over our valley region during midafternoons of bright sunshine may nearly attain adiabatic equilibrium, nevertheless the surface layers on the hillsides rarely or never reach this state, because the strong surface heating maintains the upper layers for the time being at too high a temperature; higher, in fact, possibly, than the adjacent free air at approximately the same level. An interesting result of this abnormality will be discussed further on.

10. As soon as surface cooling has once fairly set in with the decline and setting of the sun, the convective ascent of heated air at once stops or is confined to very narrow limits. At this stage the whole mass of entirely free air is relatively warm and probably almost, but not quite, in the adiabatic state. These free-air masses, however, so long as they remain in place can lose their heat only by the slow process of gaseous radiation. Radiation from the soil and vegetal cover, however, is much more rapid. Consequently, the surface layers of air everywhere on the hillsides and in the valleys lose temperature rapidly and are soon too cold to be in adiabatic relation with any of the free air. While strictly speaking the rate of loss of heat by radiation should be slightly greater the greater

the elevation, nevertheless the small advantage on this account in favor of more rapid cooling in the higher levels is quite inadequate to materially diminish the original relative excess of heat in the surface layers on the upper slopes. We may fairly say the rate of cooling by radiation of the surface air from top to bottom of the slope is practically the same when the conditions of surface cover and other things are the same. The surface air at the bottom of the slope is relatively colder to begin with than any of the surface air higher up and continues to remain so.

11. Observations at Mount Weather show that the surface air at the crest of the ridge is materially warmer, potentially, than the air lower down or at the bottom of the valley, especially as night approaches. In fact, the observations indicate that by nightfall, for a short time at least, the whole surface layer of air on the hillside from top to bottom has practically the same temperature.

12. With all the foregoing considerations in mind we are forced to the conclusion that air drainage on a hillside is very unlike the flow of water on the same slope. What takes place may be described as follows: The surface air at the bottom of the valley, cooled by its contact with the soil and cooling vegetal cover, remains practically where it is and continues throughout the night to get colder and colder, undergoing, of course, a small contraction in volume. The layers of free air immediately above the vegetal cover and cold surface air at the bottom of the valley at first remain relatively warm, because, having no contact with cooling surfaces, such free air cools chiefly by radiation and at a very small rate. At the sides of the valley, however, this relatively warm free air is closely adjacent to the cold and cooling surface layers at the same and slightly higher levels. A convective exchange of place of these portions of air begins as soon as small differences of density occur. The cool surface air from the slopes flows or drains slowly down and out, nearly horizontally on top of the colder denser air already filling the bottom of the valley. The warm free air moves in upon the slopes and in turn is itself cooled by contact with the surface cover only to exchange again with warmer adjacent free air. A similar interchange between the cooling surface air in contact with the hillside and warmer adjacent free air will take place in each succeeding higher and higher level.<sup>2</sup> Thus a continuous interchange is established probably by numerous fluctuating streams of flow between the cooling surface air at the sides of the hill and the great reservoir of warm free air of the valley.

13. It is not to be supposed that relatively small portions of slightly cooled air, retaining individuality, flow from the hillsides to positions far out in the free air. Every leaf, twig, blade of grass, or other object freely exposed skyward acts as a slow cooling agent to the small portions of immediately contiguous air. Numerous small streams of flow must necessarily exist. Intermixing at the separating surfaces of flow at once sets in and, aided by dynamic heating, not only warms up the cooler air and cools down the warmer air but tends to stop the motion. Nevertheless the average temperature of the mixture is lower than that of the other air near by, so that progressive interchanges keep going on. In the meantime the hillside, acting as a cooling agent, is continually dissipat-

<sup>2</sup> Data are lacking from which to determine the probable distance between the different strata of convective exchange. This difference will depend partly on how rapidly cooling takes place on the hillsides and partly on how greatly the temperature gradient differs from the adiabatic. For the present purpose the rate of cooling is relatively slow, consequently slow convective motions will occur for small differences of temperature and density. Since the temperature gradient in the surface layers is widely different from the adiabatic, any considerable descent of slightly cooled air along the surface or otherwise is impossible; the interchange with the warmer air must take place at many different levels, which no doubt frequently shift positions with temporary changes in rates of cooling or with any one of many other disturbing influences that may arise.

ing the heat brought in and adding new quotas of ever colder and colder air to keep up the circulation.

14. Under certain conditions it may sometimes occur during the afternoon or early evening that the surface air high up on the hillside is warmer than the adjacent free air. These temperature relations will cause the warm surface air to convectively change places with the adjacent cool free air, and to this extent the rate of cooling of the surface air on the upper portion of such slopes will be increased for a time. Just as soon, however, as the temperature of this surface air has become the same as that of the adjacent free air at nearly the same level, the convective exchange, with a cooling effect, will cease, but a similar exchange will set up again in the reverse direction with a warming effect when the temperature of the surface layers has been reduced still lower as a result of radiation.

15. It therefore appears that during the nighttime the warm free air facing the slopes of a valley, acts as a great reservoir of heat which is drawn upon by the operation of the convective exchanges described in the foregoing to conserve the temperature of the adjacent hillsides and to prevent the fall of temperature that would otherwise result from the loss of heat by nocturnal radiation under clear skies—a fall that does occur at the bottom levels of the valley where convective exchanges are impossible or the quantity of free air is too small to afford material protection. The circulation described also forms, little by little during the nighttime, the stagnant river or lakelike mass of cold air that fills the lower levels of the valley to a greater and greater depth.

16. The surface of the river of cool air is defined by the simple condition that its temperature is greater than that of any adjacent air either above or below. This surface, moreover, is essentially horizontal except along the shore lines where the surface rises to meet the bank tangentially. In this region cooling is going on somewhat rapidly and the adjustment to equilibrium is not as yet complete. The shore lines of this river in the early morning hours locate the much desired thermal belt of the orchardist. How deep the river will be at dawn under average climatic conditions in a given valley, can best be established only by suitable observations and interpolations, although estimates thereof may probably be made from a careful study of the several physical elements of the problem.

17. The foregoing clearly indicates, it is believed, the essential characteristics and principles of air drainage as it actually occurs under hill and valley conditions, and the reasons thereof. Many minor details have necessarily been omitted, and the differences in results with essentially different conditions of topography, while affording interesting applications of the principles presented above, are not appropriate to the present discussion. The point of chief importance, perhaps, is the fact that the source of the heat that conserves the temperature of the slope surfaces is the great volume of warm *free* air facing the slope. The volume of this air near the bottom of the valley, as already stated, is too small to give material protection, such as is afforded at intermediate levels. While unlimited masses of free air may be available higher up, the temperature in these levels, even at midafternoon, may be lower than that of the adjacent surfaces. Consequently at first these are rapidly cooled by both radiation and the convective exchanges. Later on these exchanges have a warming effect and conserve the surface temperatures against radiation losses, but the actual temperature may be much below the requirements of agriculture.

## VII.

## PROTECTION AGAINST FROST IN GEORGIA.

By CHARLES F. VON HERRMANN, Section Director.

[Dated Weather Bureau, Atlanta, Ga., Nov. 27, 1914.]

The first shipment of peaches from Georgia by refrigerator cars on a commercial scale was made in 1884. The rapid increase of the industry is probably best indicated by the comparative number of trees of bearing age, since variations in the quantity of product is so largely dependent upon favorable or unfavorable climatic conditions. The number of peach and nectarine trees in Georgia in 1890 was 2,787,546, in 1900 it was 7,668,639, and in 1910, 10,609,119. The total value of orchard fruits produced annually now exceeds \$3,000,000.

The principal peach-growing districts of Georgia lie northwest and south of Atlanta. According to the census of 1910 the number of peach trees in each county in the main sections were as follows:

Northwestern section.		Fort Valley district.	
County.	Number.	County.	Number.
Walker.....	283, 000	Spalding.....	127, 000
Chattooga.....	436, 000	Upson.....	195, 000
Whitfield.....	269, 000	Monroe.....	145, 000
Floyd.....	411, 000	Meriwether.....	142, 000
Gordon.....	322, 000	Crawford.....	378, 000
Bartow.....	586, 000	Taylor.....	271, 000
Pickens.....	187, 000	Macon.....	576, 000
Cherokee.....	163, 000	Jones.....	432, 000
Cobb.....	281, 000	Houston.....	1, 385, 000

The development of methods of protection from frost has kept pace with the rapid growth of horticultural interests in Georgia. An impetus was given to the study of this question by the accidental production of a full crop of peaches in one orchard near Fort Valley in 1888, while the crop was a general failure throughout the State on account of late spring frosts. The woods west of this orchard (the Hiley orchard) were accidentally fired the night before the frost, and thick smoke settled over the orchard which helped to produce a full crop of peaches. A limb containing 35 peaches cut from an Elberta tree in the Hiley orchard was photographed and for many years figured in all the nursery catalogues.

Ten years later, in 1898, the use of smudge fires as the most efficient and practical means of protection from frost was quite general in Georgia, with varying degrees of success. The fuel most frequently used was coal tar with pine straw, and 20 to 25 fires to the acre were needed to produce a sufficiently dense smoke.

The severe freeze of February, 1899,<sup>1</sup> during which temperatures below zero, Fahrenheit, were experienced even to the southern limit of the State and which resulted in the death of many trees, marked decline in the shipment of peaches, and seems to have discouraged further efforts to protect the peach crop. Since 1899 the following years only have given full crops without the necessity for protection, viz: 1901, 1904, 1908, 1912, and 1914.

During the remaining 10 years the crop was generally a partial or complete failure on account of freezing weather in early spring or late frosts. The whole matter of protecting peaches in Georgia is now in a state of

<sup>1</sup> See MONTHLY WEATHER REVIEW, February, 1899, p. 69, and Chart XIII.